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Special Technical Report 16

A NOTE ON THE COMPUTED RADIATION PATTERNS OF DIPOLE ANTENNAS IN DENSE VEGETATION

By: JOHN TAYLOR

Prepared for:

U.S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERSEY

CONTRACT DA 36-039 AMC-00040(E)
ORDER NO. 5384-PM-63-91
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STANFORD RESEARCH INSTITUTE

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SRI Project 4240

Approved: W. R. VINCENT, MANAGER
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ELECTRONICS AND RADIO SCIENCES

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ABSTRACT

A mathematical model of a short dipole antenna in a homogeneous, isotropic forest medium is developed. Height gain function and directivity patterns at HF are calculated for two cases, antenna in the open and in a forest, and these calculations are compared with some preliminary airborne measurements made with resonant dipoles. Excellent agreement between calculated and measured patterns and gain is obtained. Dipole gain at low elevation angles is found to increase in the forest (over the open-field case).

Permutation of the six parameters of the model (permittivity and loss tangent of both earth and forest, antenna height, and forest height) indicates that the effect of antenna height (h_a) is the most significant. The forest height and permittivity of the forest become important at the very low elevation angles, and the loss tangent of the earth becomes important at low antenna heights ($h_a < \lambda/10$). The dielectric constant of the ground and loss tangent of the forest are apparently relatively unimportant variables when checked over the ranges that seem reasonable for tropical forests.

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ILLUSTRATIONS

I INTRODUCTION

In considering antennas for use with HF, low-power, portable communications equipment in dense forest areas, it is pertinent to ask what effect the forest has on the radiation patterns. We know that the attenuation of a signal transmitted through forest is so high[1,2*] that the ground wave is useless for distances of more than a mile or two. We are thinking, therefore, of a short-range sky-wave link in which the signal travels almost vertically to the ionosphere and back to the receiver, which may be up to 25 or 50 miles away. The distance along the ground is relatively unimportant, since the path for a 5-mile range is very nearly the same as that for a 50-mile range.

Antenna types for this use must be small enough and light enough to be easily carried and simple enough to be quickly erected. The type that first comes to mind is a short horizontal dipole. The simplicity of this antenna makes it very attractive, and wide experience with it leads one to believe that it will be one of the better types for our use. We must therefore give it careful consideration and determine what effect compromises with such parameters as antenna length and antenna height above ground will have on overall system performance.

For the sky-wave link it is important to know the directivity in a small sector near the zenith, but why do we need the complete radiation pattern—particularly, why are we interested in the pattern at low elevation? There are several reasons for wanting the pattern at low angles: First, much of the atmospheric noise and most of the interfering signals will have low angles of arrival, and since the short-range link must operate at a frequency below the vertical-incidence critical frequency, the noise and interference may suffer considerable attenuation on the propagation path. If the forest surrounding the receiving antenna can be made to discriminate effectively against these unwanted signals, we may be able to reduce them to the point where they are no longer a serious limitation on the usefulness of the link.

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* References are given at the end of the report.

A second, but not secondary, reason for needing a thorough understanding of how the forest affects the radiation pattern stems from the fact that we are dealing with a military communication system and must expect attempts to intercept our messages, to jam our link, and to use direction finders for locating our transmitters. The success of any of these enemy countermeasures will be largely dependent on the low-angle directivity of the antenna we use. Inasmuch as an HF link is particularly vulnerable to interception and to jamming from distant locations, it is very important to reduce the low-angle radiation, if possible.

In investigating the effect of the forest on radiation patterns, we need to pursue both a measurements approach and an analytical approach. A measurements program alone is insufficient because there are too many variables and we cannot hope to measure the range of situations in which we are interested. An analytical study alone is also insufficient at this stage because of our inability to construct a mathematical model in which we have full confidence. This report is concerned with the analytical approach.

II THE MODEL OF THE FOREST

The model we have chosen for our analysis is a dielectric sandwich (Fig. 1) in which the upper region is the space above the forest, characterized by ϵ_0 and μ_0, the permittivity and permeability of free space. The center region is the forest, characterized by a complex dielectric constant,

$$\epsilon_1 = \epsilon_1' - j\epsilon_1'' \quad ,$$

and the lower region is the ground below the forest, characterized by a complex dielectric constant

$$\epsilon_2 = \epsilon_2' - j\epsilon_2'' \quad .$$

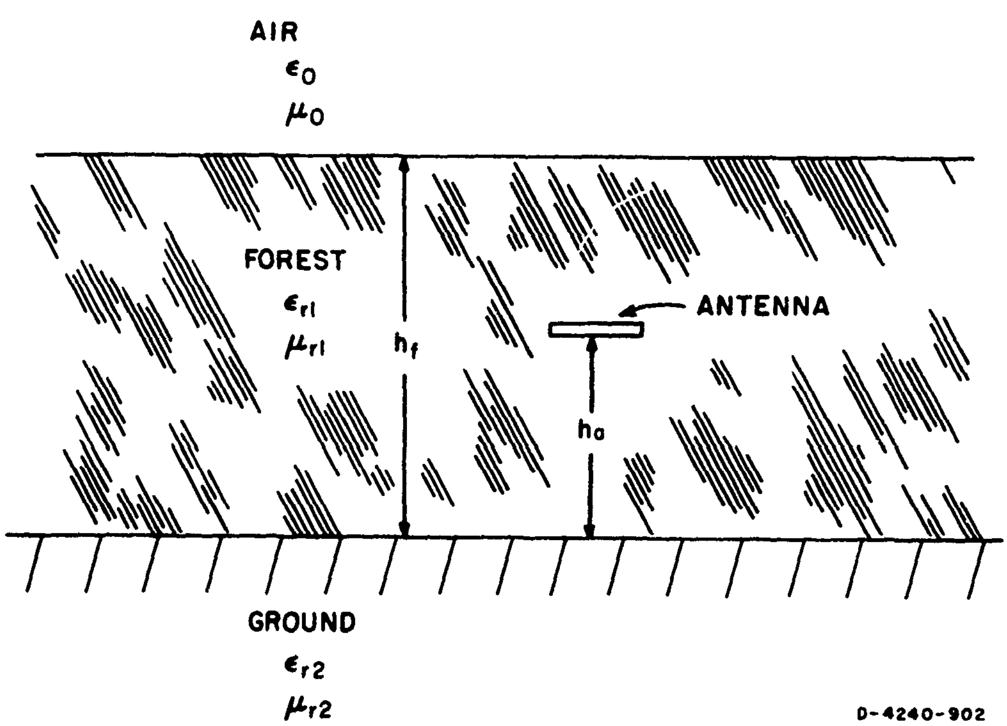

FIG. 1 IDEALIZED LOSSY DIELECTRIC SLAB MODEL

Alternatively, the complex dielectric constant can be written

$$\epsilon_i = \epsilon_i'(1 - j\delta_i) \quad ,$$

where the loss tangent, δ_i, is defined by

$$\delta_i = \frac{\epsilon_i''}{\epsilon_i'} \quad .$$

Each region is assumed to be homogeneous and to possess the magnetic permeability of free space.

This model, although simple, probably represents the forest quite well in the frequency range of 2 to 10 Mc/s, and its simplicity permits a reasonably rigorous analysis. The assumption of a flat surface on the top is justifiable when one considers that the surface roughness is small compared to the wavelength. The assumptions of isotropy and homogeneity in the vertical direction are harder to justify. It is probable that a multilayered slab or a layer with a tapered dielectric constant, lower at the top than at the bottom, would be a better approximation to the forest. Aside from the fact that a tapered dielectric constant would complicate the analysis, it is difficult at this time to find enough data on the dielectric constant and loss tangent of a forest to choose one value for each of these parameters,[3] much less to specify how they should vary with height. We have therefore chosen the simple model of a uniform layer.

III THE ANALYSIS

In analyzing the problem, we will consider the antenna element and the dielectric layers as an antenna system radiating into the half-space above. For convenience we will also assume that the antenna in the forest is receiving a signal. The radiation patterns, of course, are identical with those of the antenna when it is used in transmitting.

For our far-zone approximations to be valid, the transmitting antenna must be far enough away from the receiving antenna so that the wavefront across the aperture is approximately plane. If, for example, it is assumed that the effective aperture is a region about 4 wavelengths in diameter (D_a) centered at the receiving antenna element, and if the usual far-zone criterion, $r \geq 2D_a^2/\lambda$, is used, then the transmitting antenna must be at least 4.8 km or approximately 3.5 miles away at a frequency of 2 Mc/s. Actually, the effective aperture of the antenna and its surrounding vegetation should be measured.

For an electrically short dipole with large capacitive end loading, the open-circuit voltage at the antenna terminals is the product of the antenna length and the component of electric field in the direction of the antenna axis. For a short dipole with no end loading, the voltage is one-half of this value. But the open-circuit voltage of a receiving antenna is:

$$Voc = \overline{h}(\theta,\phi) \cdot \overline{E}(\theta,\phi) \quad ,$$

where $\overline{E}$ is the incident electric field, and $\overline{h}(\theta,\phi)$ is the *vector effective length.*[4] Hence, we can find $\overline{h}(\theta,\phi)$ from the field in the dielectric and the physical length of the antenna. The radiation patterns given in this report are the ratio of $|\overline{h}|$ to the physical half-length of the dipole with no end loading. It is interesting to note that the far-zone field of the antenna when it is used in transmitting is

$$\overline{E}(\theta,\phi) = j\frac{\omega\mu_0 e^{-jkr}}{4\pi r} I_0\overline{h}(\theta,\phi) \quad ,$$

where

$\overline{E}(\theta,\phi)$ = electric field at distance r in the θ,ϕ direction

ω = $2\pi f$ = radian frequency

μ_0 = magnetic permeability of free space

r = distance from transmitting antenna phase center to point of measurement of electric field

I_0 = antenna current

k = $2\pi/\lambda$ = wave number

λ = wavelength

and

$\overline{h}(\theta,\phi)$ is defined as above.

We have thus reduced the problem of finding the antenna patterns to that of finding the electric field within the dielectric layer representing the forest.

Using the coordinates shown in Fig. 2, we find that the pattern of a horizontal dipole in the plane perpendicular to the dipole is given by the electric field, E_{1z}, of a wave polarized normal to the plane of incidence. For a wave polarized in the plane of incidence, E_{1x} is the

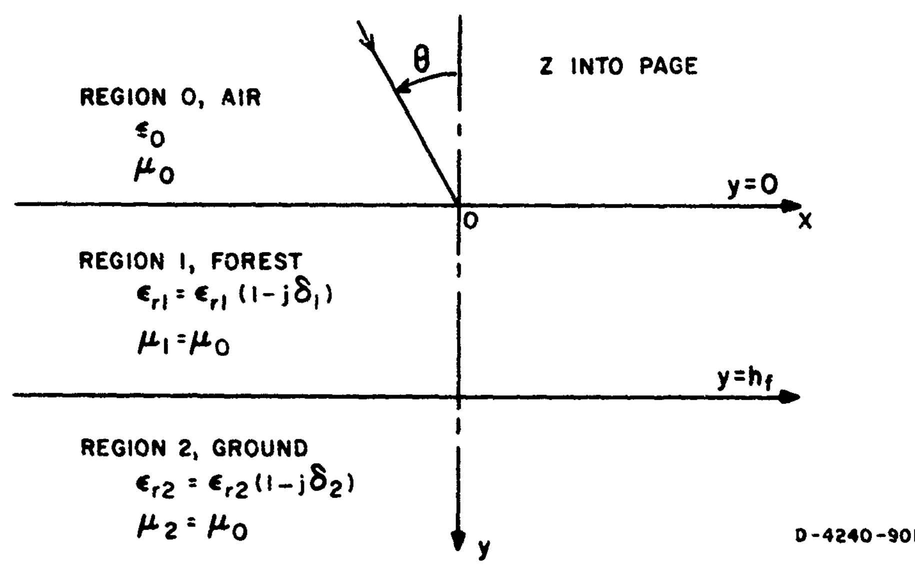

FIG. 2 COORDINATES AND NOMENCLATURE FOR DIELECTRIC SLAB

pattern of a horizontal dipole in the plane of the dipole, and E_{1y} is the pattern of a vertical dipole in the plane of the dipole.

For a wave polarized normal to the plane of incidence, appropriate solutions of Maxwell's equations for the three regions are:

Region 0:

$$\overline{E}_0 = \overline{E}_i + \overline{E}_r$$

$$\overline{E}_i = \hat{z}e^{-j(x\sin\theta + y\cos\theta)}$$

$$\overline{H}_i = \frac{1}{\zeta_0}[\hat{x}\cos\theta - \hat{y}\sin\theta]e^{-j(x\sin\theta + y\cos\theta)}$$

$$\overline{E}_r = \hat{z}Re^{-j(x\sin\theta - y\cos\theta)}$$

$$\overline{H}_r = -\frac{R}{\zeta_0}[\hat{x}\cos\theta + \hat{y}\sin\theta]e^{-j(x\sin\theta - y\cos\theta)} .$$

Region 1:

$$\overline{E}_1 = \hat{z}[Ae^{-\gamma_1 y} + Be^{\gamma_1 y}]e^{-jx\sin\theta}$$

$$\overline{H}_1 = -\left[\hat{x}j\frac{\gamma_1}{\zeta_0}(Ae^{-\gamma_1 y} - Be^{\gamma_1 y}) + \frac{\hat{y}\sin\theta}{\zeta_0}(Ae^{-\gamma_1 y} + Be^{\gamma_1 y})\right] \cdot [e^{-jx\sin\theta}] .$$

Region 2:

$$\overline{E}_2 = \hat{z}Te^{-\gamma_2(y-h_f)}e^{-jx\sin\theta}$$

$$\overline{H}_2 = -\frac{T}{\zeta_0}[\hat{x}j\gamma_2 + \hat{y}\sin\theta]e^{-\gamma_2(y-h_f)}e^{-jx\sin\theta} .$$

In these solutions the fields have been normalized so that

$$|\overline{E}_i| = 1 ,$$

and all propagation constants have been normalized so that

$$k_0 = 1 .$$

Distances are given in radians at the free-space wavelength. The symbols are defined in the Appendix.

When the wave is polarized in the plane of incidence, the appropriate solutions in the three regions are:

Region 0:

$$\overline{E}_0 = \overline{E}_i + \overline{E}_r$$

$$\overline{E}_i = (\hat{x}\cos\theta - \hat{y}\sin\theta)\,e^{-j(x\sin\theta + y\cos\theta)}$$

$$\overline{H}_i = \frac{-\hat{z}}{\zeta_0}\,e^{-j(x\sin\theta + y\cos\theta)}$$

$$\overline{E}_r = R(\hat{x}\cos\theta + \hat{y}\sin\theta)\,e^{-j(x\sin\theta - y\cos\theta)}$$

$$\overline{H}_r = \frac{\hat{z}R}{\zeta_0}\,e^{-j(x\sin\theta - y\cos\theta)} \quad .$$

Region 1:

$$\overline{E}_1 = \left[j\,\frac{\hat{x}\zeta_0\gamma_1}{\epsilon_{r1}}\,(Ae^{-\gamma_1 y} - Be^{\gamma_1 y}) + \frac{\hat{y}\,\zeta_0\sin\theta}{\epsilon_{r1}}\,(Ae^{-\gamma_1 y} + Be^{\gamma_1 y})\right]e^{-jx\sin\theta}$$

$$\overline{H}_1 = \hat{z}\,[Ae^{-\gamma_1 y} + Be^{\gamma_1 y}]\,e^{-jx\sin\theta} \quad .$$

Region 2:

$$\overline{E}_2 = \frac{\zeta_0 T}{\epsilon_{r2}}\,[j\hat{x}\gamma_2 + \hat{y}\sin\theta]\,e^{-\gamma_2(y-h_f)}\,e^{-jx\sin\theta}$$

$$\overline{H}_2 = \hat{z}\,Te^{-\gamma_2(y-h_f)}\,e^{-jx\sin\theta} \quad .$$

For both polarizations the propagation constants

$$\gamma_1 = \alpha_1 + j\beta_1$$

and

$$\gamma_2 = \alpha_2 + j\beta_2$$

must satisfy the equations

$$\gamma_1^2 + k_1^2 - k_0^2 \sin^2\theta = 0$$

and

$$\gamma_2^2 + k_2^2 - k_0^2 \sin^2\theta = 0$$

as a consequence of the fact that the vectors $\overline{E}$ and $\overline{H}$ are solutions of the wave equation,

$$\nabla^2\overline{E} + k^2\overline{E} = 0 \quad .$$

The real and imaginary parts of γ for Region 1 are given, then, by

$$\alpha_1^2 = 1/2 \left[(\sin^2\theta - \epsilon'_{r1}) + \sqrt{(\epsilon'_{r1} - \sin^2\theta)^2 + (\epsilon'_{r1}\delta_1)^2} \right]$$

$$\beta_1 = \begin{cases} \dfrac{\epsilon'_{r1}\delta_1}{2\alpha_1} & , \quad \text{for} \quad \alpha_1 \neq 0 \\[2ex] \sqrt{\epsilon'_{r1} - \sin^2\theta} & , \quad \text{for} \quad \alpha_1 = 0 \end{cases} \quad .$$

In Region 2, α_2 and β_2 are obtained from the same equations, with ϵ'_{r1} and δ_1 replaced by ϵ'_{r2} and δ_2, respectively.

For both polarizations the requirement that the tangential components of the vectors $\overline{E}$ and $\overline{H}$ be continuous across the two boundaries, $y = 0$ and $y = h_f$, leads to the following set of equations from which A, B, T, and R can be determined:

$$\begin{bmatrix} 1 & 1 & 0 & -V \\ C_1 & -C_1 & 0 & jV\cos\theta \\ e^{-\gamma_1 h_f} & e^{\gamma_1 h_f} & -1 & 0 \\ C_1 e^{-\gamma_1 h_f} & -C_1 e^{\gamma_1 h_f} & -C_2 & 0 \end{bmatrix} \begin{bmatrix} A \\ B \\ T \\ R \end{bmatrix} = \begin{bmatrix} \pm V \\ \pm jV\cos\theta \\ 0 \\ 0 \end{bmatrix} \quad .$$

For polarization normal to the plane of incidence,

$$= 1$$

$$C_1 = \gamma_1$$

$$C_2 = \gamma_2$$

and the plus signs in the matrix on the right pertain.

When the wave is polarized in the plane of incidence,

$$V = \frac{1}{\zeta_0}$$

$$C_1 = \frac{\gamma_1}{\epsilon_{r1}}$$

$$C_2 = \frac{\gamma_2}{\epsilon_{r2}}$$

and the minus signs in the matrix on the right must be used.

The resulting field patterns for short electric dipoles in Region 1 (forest) are:

(1) Horizontal dipole in plane normal to dipole:

$$F_1(\theta) = |E_{1z}| \qquad \text{(for polarization normal to the plane of incidence)}$$

Thus

$$F_1(\theta) = \frac{2\cos\theta \left| W_1 e^{\gamma_1 h_a} - W_2 e^{-\gamma_1 h_a} \right|}{\left| C_1\left(W_1 e^{\gamma_1 h_f} + W_2 e^{-\gamma_1 h_f}\right) + j\cos\theta\left(W_1 e^{\gamma_1 h_f} - W_2 e^{-\gamma_1 h_f}\right) \right|}$$

where

$$W_1 = C_2 + C_1$$

and

$$W_2 = C_2 - C_1 \quad .$$

(2) Horizontal dipole in plane of dipole:

$$F_2(\theta) = |E_{1x}| \quad \text{(for polarization in plane of incidence).}$$

Hence

$$F_2(\theta) = \frac{2\cos\theta \left| C_1\left(W_1 e^{\gamma_1 h_a} + W_2 e^{-\gamma_1 h_a}\right)\right|}{\left| C_1\left(W_1 e^{\gamma_1 h_f} + W_2 e^{-\gamma_1 h_f}\right) + j\cos\theta\left(W_1 e^{\gamma_1 h_f} - W_2 e^{-\gamma_1 h_f}\right)\right|} .$$

(3) Vertical dipole in plane of dipole:

$$F_3(\theta) = |E_{1y}| \quad \text{(for polarization in plane of incidence).}$$

In this case,

$$F_3(\theta) = \frac{\sin 2\theta \left| W_1 e^{\gamma_1 h_a} - W_2 e^{-\gamma_1 h_a}\right|}{|\epsilon_{r1}|\left| C_1\left(W_1 e^{\gamma_1 h_f} + W_2 e^{-\gamma_1 h_f}\right) + j\cos\theta\left(W_1 e^{\gamma_1 h_f} - W_2 e^{-\gamma_1 h_f}\right)\right|} .$$

In using the equations to compute antenna patterns, note that the values of C_1 and C_2 and hence of W_1 and W_2 depend on the polarization of the incident wave.

The patterns of a small loop antenna (small compared to the wavelength) can be found from the components of the magnetic field.

IV RADIATION PATTERNS

The function F_1 is the pattern of a horizontal dipole in the plane normal to the dipole; F_2 is the pattern of a horizontal dipole in the plane of the dipole; and F_3 is the pattern of a vertical dipole in the plane of the dipole. In all cases the patterns are normalized so that F is the ratio of the effective length of the antenna to its physical half-length. The antenna is assumed to be short compared to the wavelength of the radiated signal and to have no end loading.

The effective length, $\overline{h}$, affords a comparison of the field strengths from transmitting antennas, under the constraint that the input current is constant. The functions, F, thus compare the field of a dipole in the forest above a plane ground (or above a plane ground with no forest) with that of the same dipole in free space carrying the same input current. It is often more pertinent to the transmitting problem, however, to compare the fields, or power densities, under the constraint that the input power to the antenna is constant. The gain function, $G(\theta,\phi)$, gives this comparison. Thus

$$p(\theta,\phi) = \frac{P}{4\pi r^2} G(\theta,\phi) \quad ,$$

where $p(\theta,\phi)$ is the power density in the transmitted wave; P is the input power to the antenna; and r is the distance in the θ,ϕ direction.

The gain function is the product of the directivity function, $D(\theta,\phi)$, and the power transfer efficiency, η:

$$G(\theta,\phi) = \eta D(\theta,\phi) \quad .$$

Now for a linearly polarized antenna:

$$G(\theta,\phi) = \frac{\pi\zeta}{Ra}\left[\frac{h(\theta,\phi)}{\lambda}\right]^2 \quad ,$$

where Ra is the input resistance to the antenna, and ζ is the characteristic impedance of the medium in which the antenna is immersed. This equation can be written:

$$G(\theta,\phi) = G_d [F(\theta,\phi)]^2 \left(\frac{Rd}{Ra}\right)$$

or, expressed in decibels,

$$G_{dB}(\theta,\phi) = 10 \log_{10} G_d + 20 \log_{10} F(\theta,\phi) - 10 \log_{10} \left(\frac{Ra}{Rd}\right) .$$

In this expression for the gain,

$$G_d = 1.5$$

is the maximum of the gain function for an electrically short dipole in free space, and Rd is the input resistance of this antenna in free space.

To compute the gain function of a dipole in the forest, we need to know the ratio, Ra/Rd, in addition to F. The input resistance, Ra, is affected quite drastically by the proximity of the antenna to ground, but one would expect the presence of the forest to have very little effect on it, particularly if the heavy vegetation is cleared for a few feet in the immediate vicinity of the antenna. Preliminary measurements in Thailand at VHF, by N. K. Shrauger and K. L. Taylor, indicate that this assumption is true. Measurements in the Hoh Rain Forest, Olympic Peninsula, Washington, at HF and VHF, by H. W. Parker, show agreement with the initial data from Thailand for a horizontal dipole. The curves of Vogler and Noble[5] for Ra/Rd should therefore be valid whether or not the antenna is in a forest, and we can use them together with F to compute the gain function.

V COMPUTED RESULTS

So many parameters have an effect on the radiation patterns that it is not feasible to compute patterns for all combinations of interest. The results shown here were obtained, therefore, by choosing typical values of each parameter and then varying them, one at a time, around this value. The parameters studied were:

(1) Antenna height (wavelengths)

(2) Dielectric constant of forest

(3) Loss tangent of forest

(4) Forest height (wavelengths)

(5) Dielectric constant of earth

(6) Loss tangent of earth.

Typical values of forest height and antenna height in wavelengths can be chosen for the range of frequencies of interest to us. A quantity of data is available on the ground constants; hence typical values for these can be chosen with reasonable certainty. On the other hand, very few data are available on the dielectric properties of a forest. From the work of Pounds and LaGrone[6] and from that of Herbstreit and Crichlow,[7] together with some recent measurements made by Parker and Hagn[3] as a part of the present research effort, it appears that the relative dielectric constant for tropical forests should be in the range of 1.05 to 1.5 and the loss tangent should be in the range of 0.02 to 0.2 at frequencies of 2 to 10 Mc/s. For this study a dielectric constant of 1.2 to 1.4 and a loss tangent of 0.1 were assumed to be typical for a very dense tropical forest. Subsequent measurements in CONUS on this program, using the open-wire transmission line, have indicated that the value for the dielectric constant may not be quite this large, whereas the value for the loss tangent at 2 Mc/s actually may be greater than 0.1 in a tropical forest.[3,8]

The most significant of the parameters studied here is the height of the antenna above ground. It affects both the input resistance and the effective length of the antenna and therefore changes the gain function

quite drastically. It is also the only one of these parameters that we can readily control in the field.

Figures 3 and 4 are polar plots of $F_1(\theta)$ and $F_2(\theta)$ with antenna height in wavelengths as a parameter. Figure 3 is for the case of no forest; Fig. 4 is for an antenna in a dense forest. To emphasize the importance of raising the antenna above the ground, the same data are presented in a different way in Figs. 5 and 6. Here F, the field function, is plotted as a function of antenna height for two specific angles, one at the zenith and one very near the horizon. The gain function (Figs. 7 and 8) varies even more rapidly with antenna height.*

Figure 9 shows the variation of antenna gain with the height of the antenna above ground, for three frequencies. The results are similar to those shown in Fig. 7 but have been translated to specific frequencies, and in this case the height is given in feet. This figure indicates how much improvement we can obtain when we raise the antenna above ground. At a frequency of 3 Mc/s, for example, raising the antenna from 2 feet above ground to 10 feet increases the gain in the direction of the zenith by 24 dB. At 6 Mc/s the improvement is 20 dB. This improvement is due to the effect of the ground and has very little to do with whether or not the antenna is in a forest (see also Fig. 15).

Figure 10 shows the effect of the denseness of the vegetation on the radiation toward the zenith and horizon. The values of F_1 and F_2 are plotted as a function of the dielectric constant of the forest. Curves are plotted for two widely different values of ground constants. As would be expected, the radiation near the zenith is very little affected. The low-angle radiation is changed quite appreciably, however, with the vertically polarized wave near the ends of the antenna being decreased as the dielectric constant increases and the horizontally polarized wave broadside to the dipole being greater than that with no forest.

In Fig. 11 the variation of F_1 and F_2 for both high-angle and low-angle radiation is plotted as a function of the loss tangent of the forest. The effect of this parameter appears to be completely negligible.

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* One would expect these curves to be smooth as are those in Figs. 5 and 6. The perturbations are probably the result of errors in reading the antenna resistance from the curves of Vogler and Noble.[5]

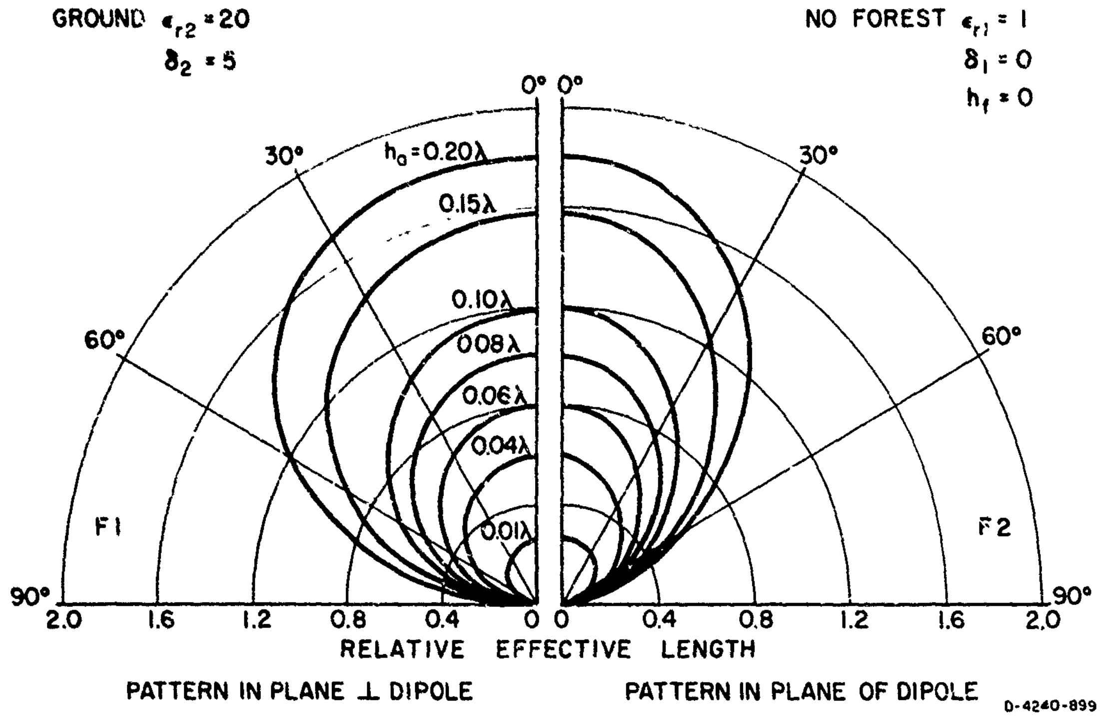

FIG. 3 EFFECTIVE ANTENNA LENGTH FOR VARIOUS HEIGHTS, h_a — NO FOREST

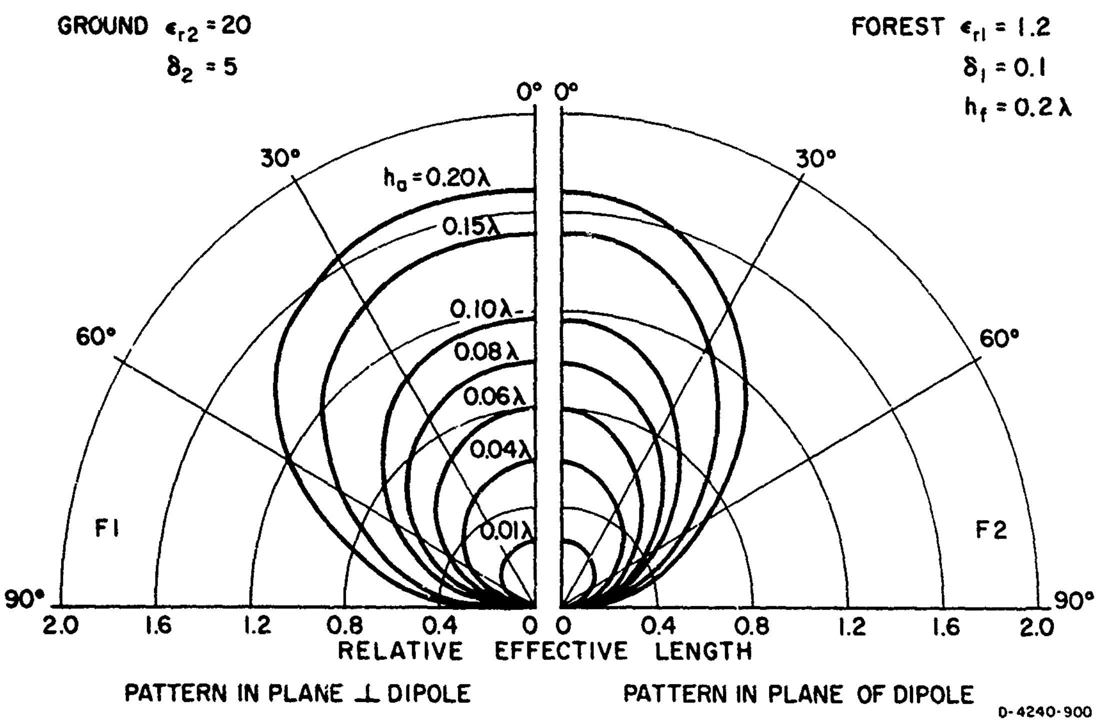

FIG. 4 EFFECTIVE ANTENNA LENGTH FOR VARIOUS HEIGHTS, h_a — FOREST

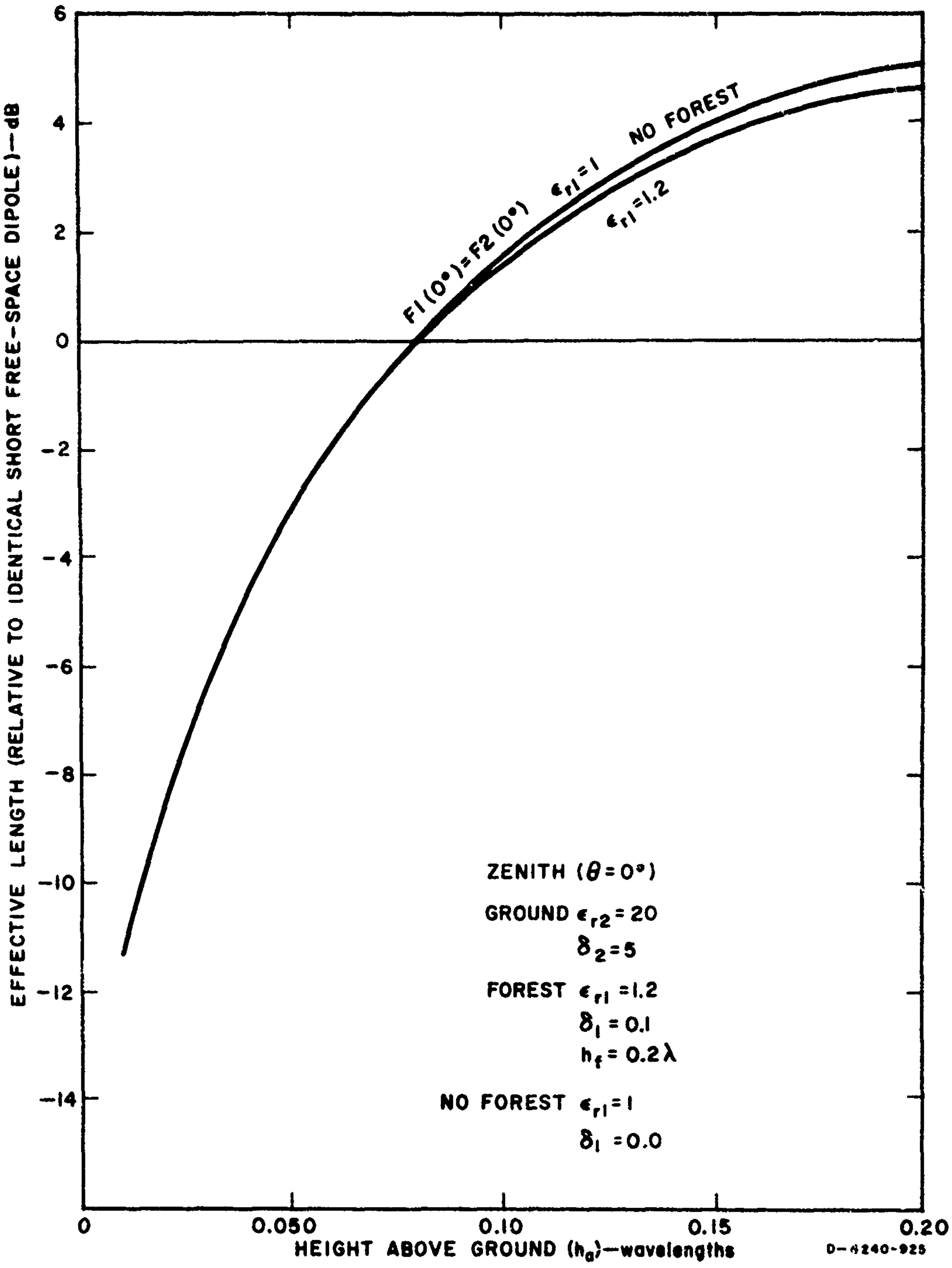

FIG. 5 EFFECTIVE ANTENNA LENGTH AS A FUNCTION OF HEIGHT ABOVE GOOD GROUND — ZENITH

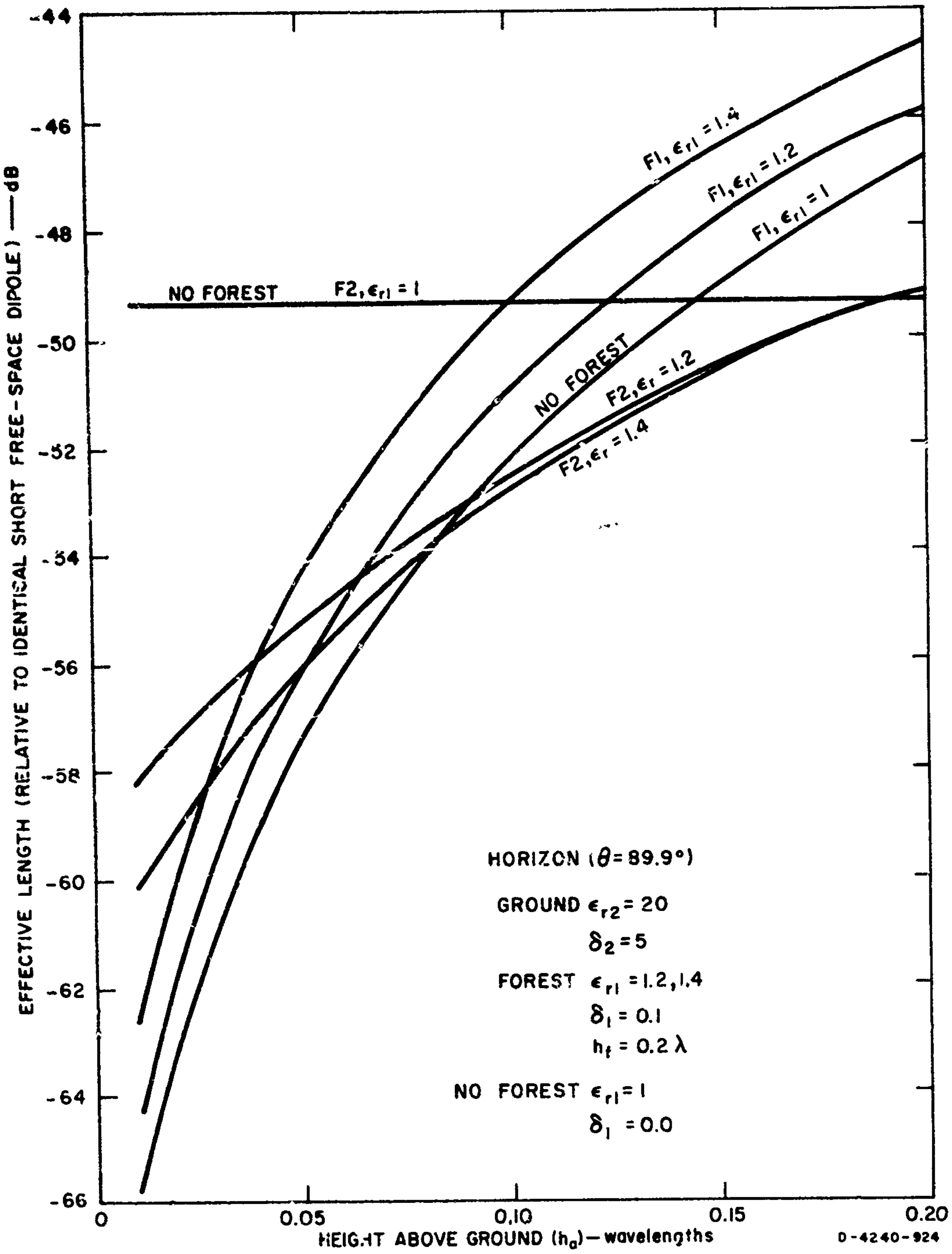

FIG. 6 EFFECTIVE ANTENNA LENGTH AS A FUNCTION OF ANTENNA HEIGHT ABOVE GOOD GROUND — HORIZON

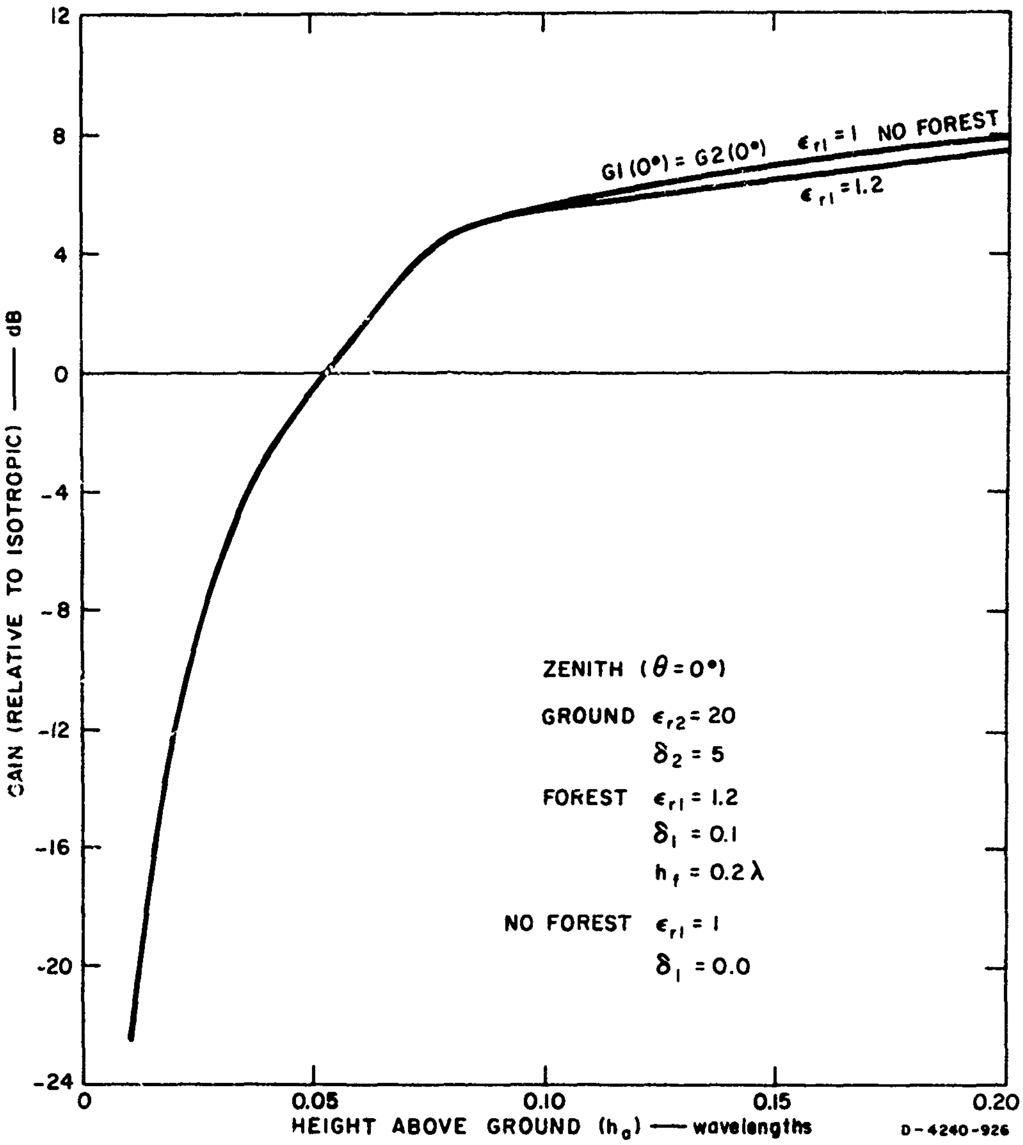

FIG. 7 GAIN AT ZENITH AS A FUNCTION OF ANTENNA HEIGHT (Wavelengths) ABOVE GOOD GROUND

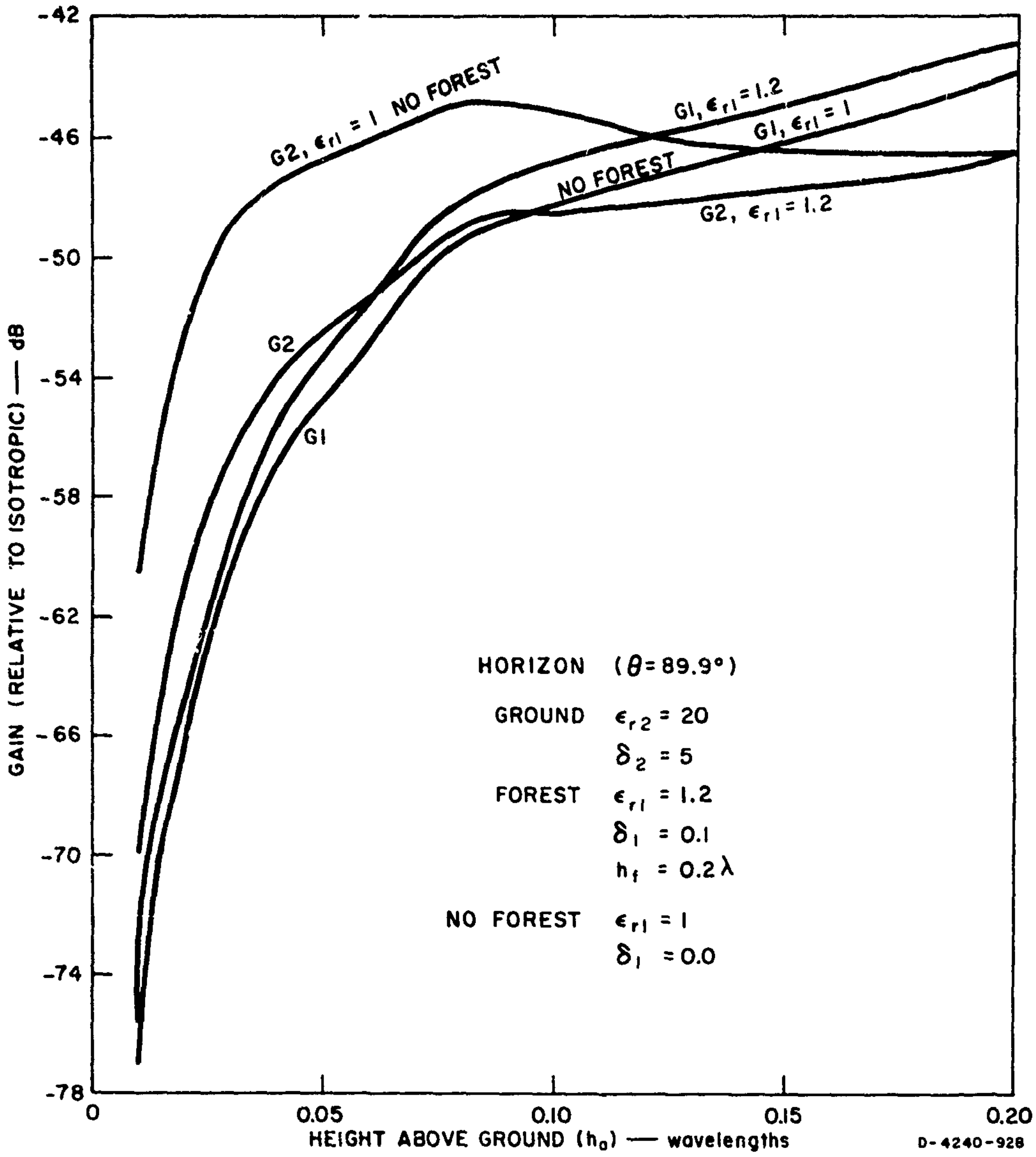

FIG. 8 GAIN AT HORIZON AS A FUNCTION OF ANTENNA HEIGHT ABOVE GOOD GROUND

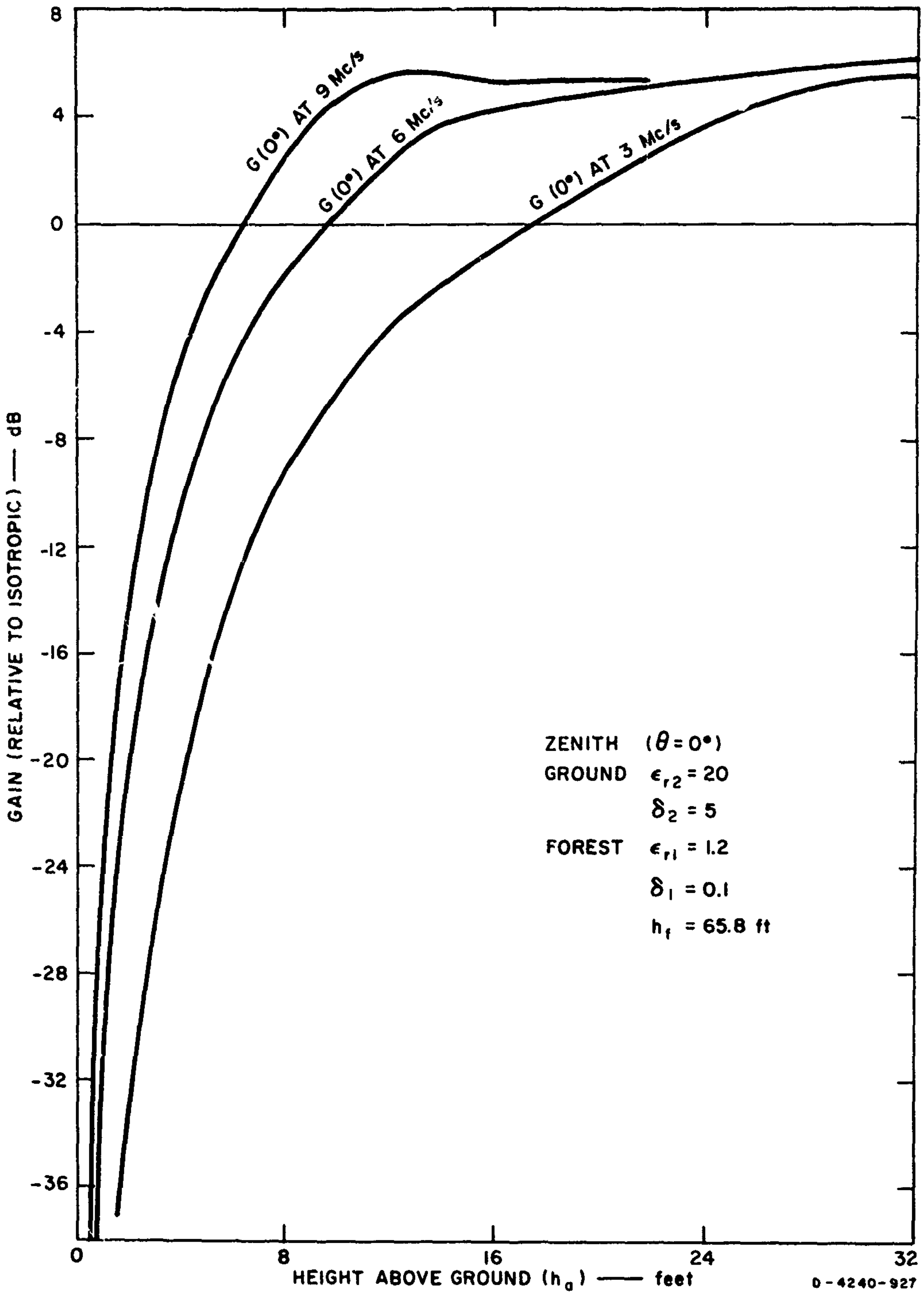

FIG. 9 GAIN AT ZENITH AS A FUNCTION OF ANTENNA HEIGHT (Feet) ABOVE GOOD GROUND

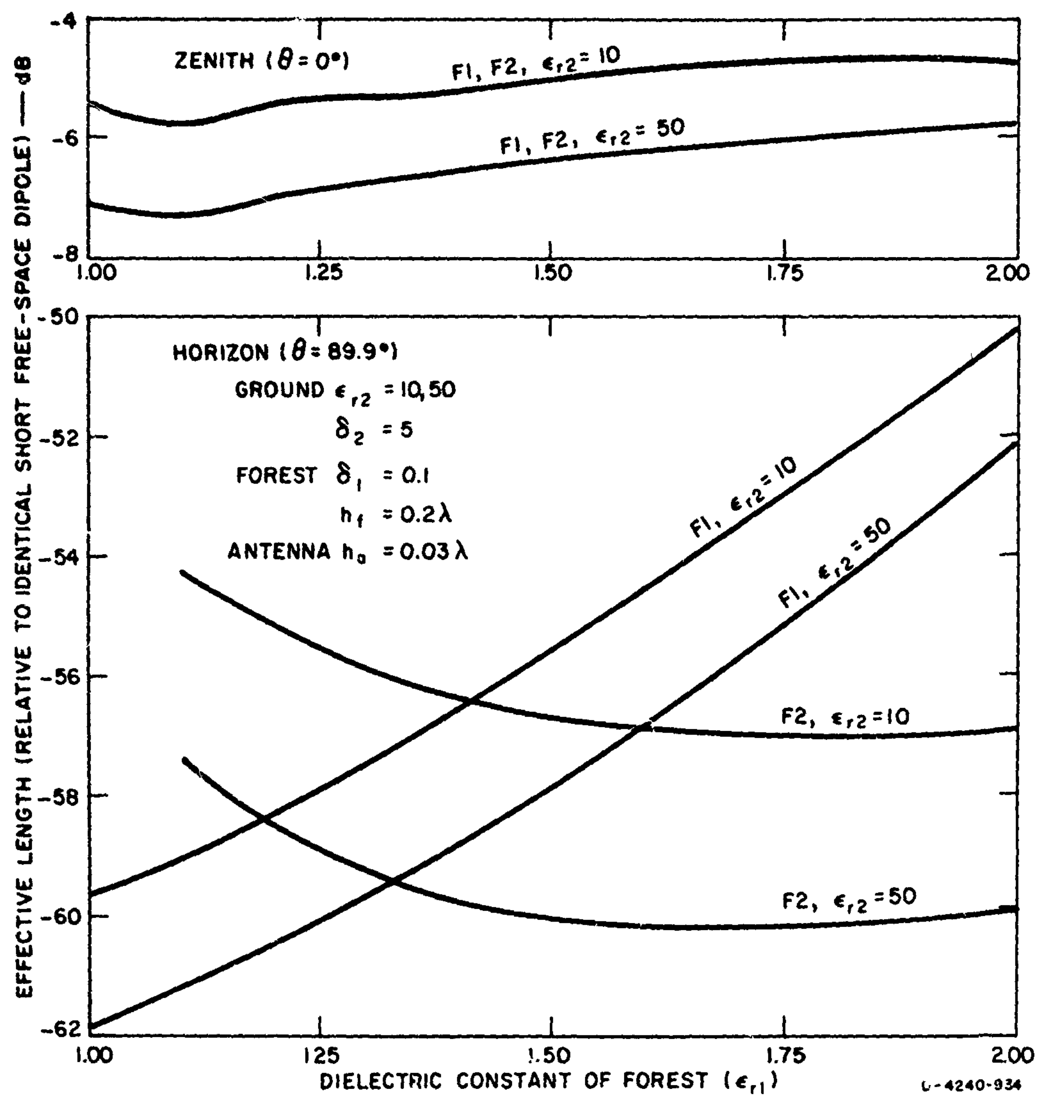

FIG. 10 EFFECTIVE ANTENNA LENGTH AS A FUNCTION OF DIELECTRIC CONSTANT OF FOREST

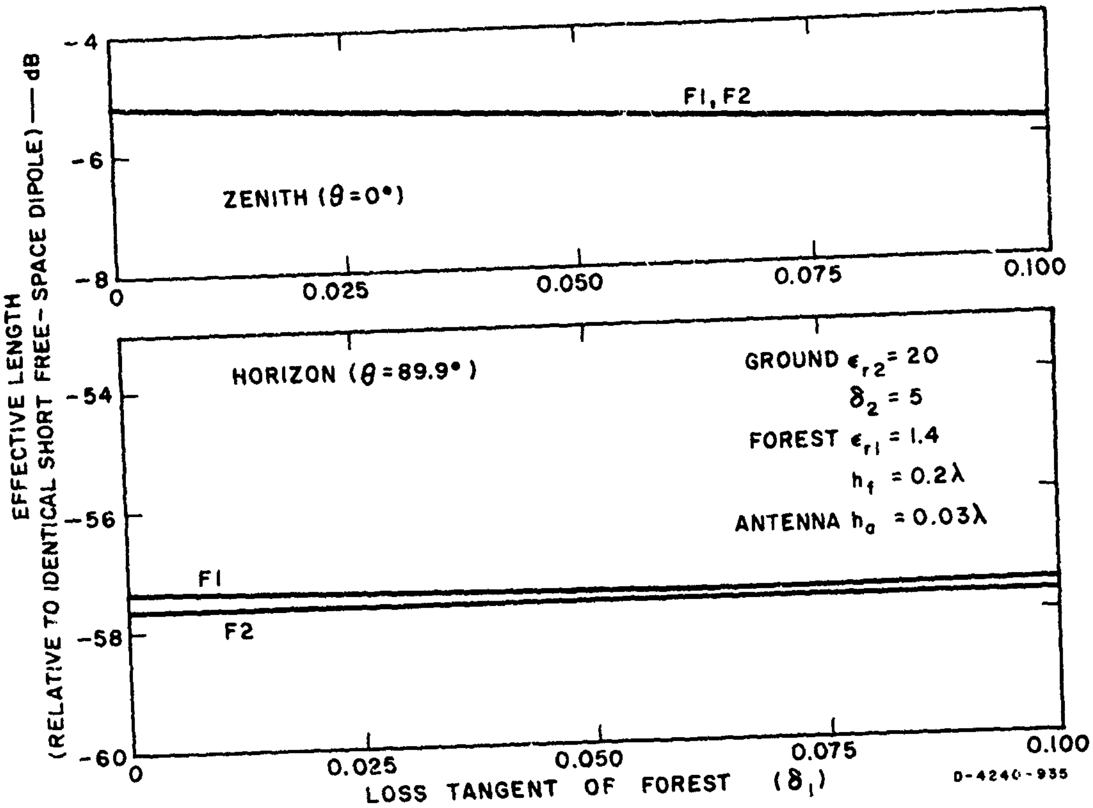

FIG. 11 EFFECTIVE ANTENNA LENGTH AS A FUNCTION OF LOSS TANGENT OF FOREST

Figure 12 shows the effect of forest height (in wavelengths) on the patterns. As in the case of the dielectric constant of the forest, the high-angle radiation is affected only slightly, while the low-angle radiation is affected rather markedly. The vertically polarized signal near the ends of the dipole decreases as forest height increases, while the horizontally polarized signal broadside to the antenna increases with forest height.

Figures 13 and 14 show the effect of ground constants on the patterns. Neither the effect of the dielectric constant nor that of the loss tangent is very marked. Note here that F_1 and F_2 vary with the same trend as the dielectric constant when it is changed, in contrast to the effect of the forest parameters.

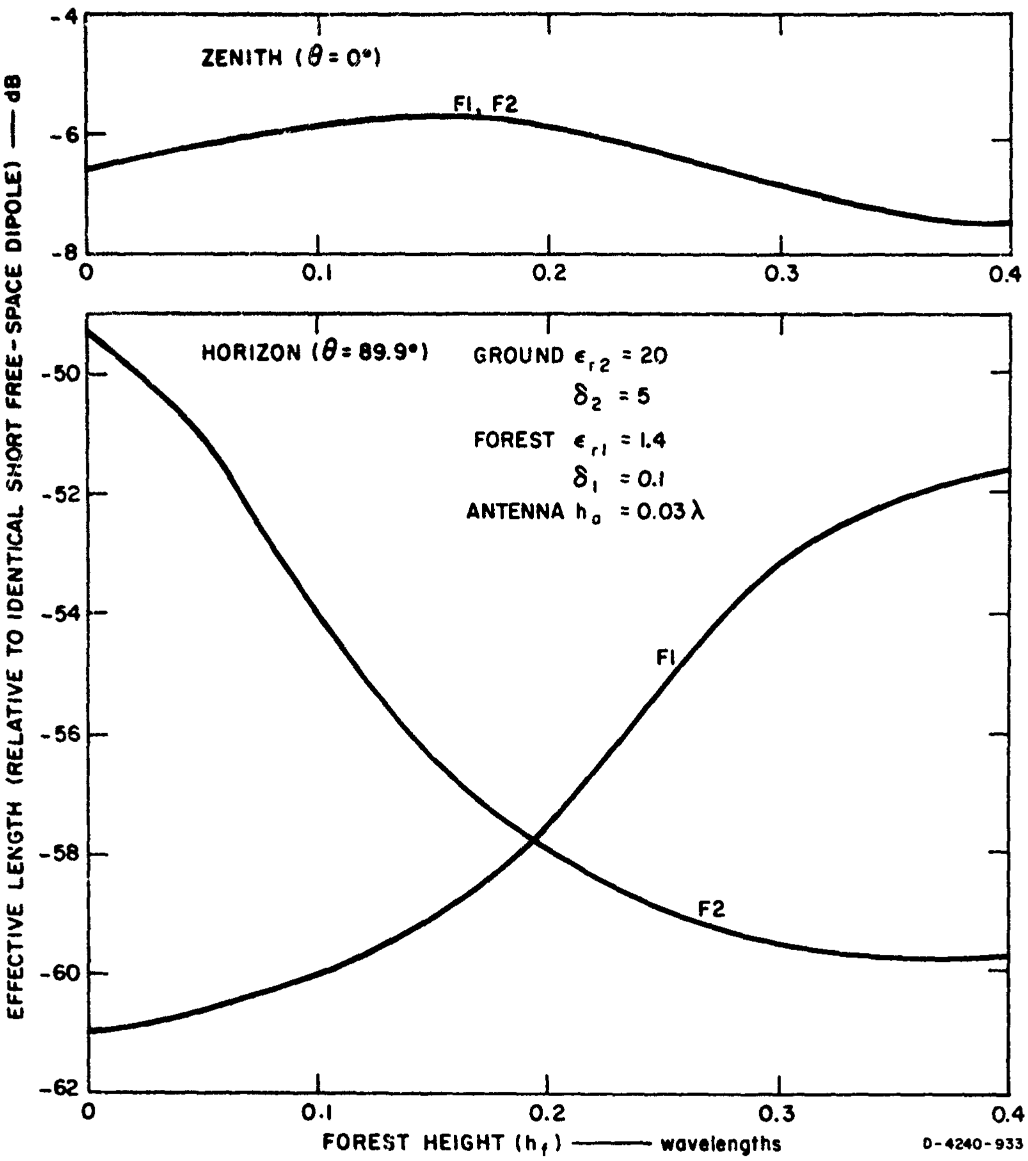

FIG. 12 EFFECTIVE ANTENNA LENGTH AS A FUNCTION OF FOREST HEIGHT

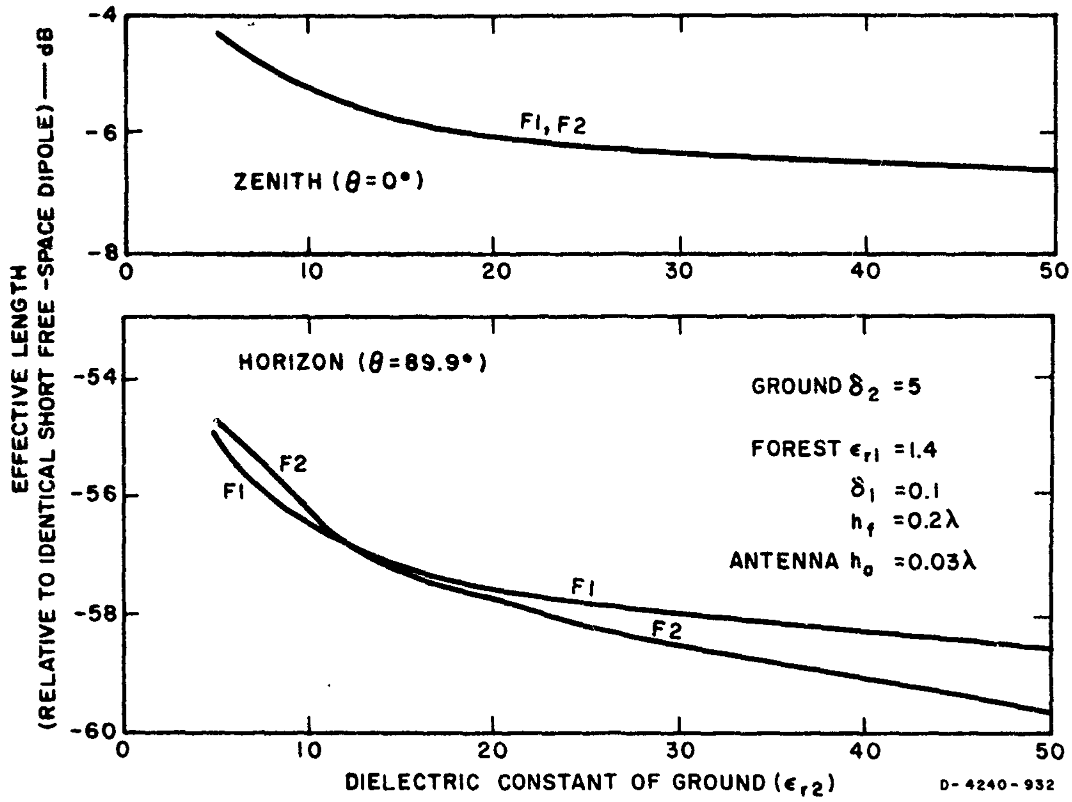

FIG. 13 EFFECTIVE ANTENNA LENGTH AS A FUNCTION OF GROUND PERMITTIVITY

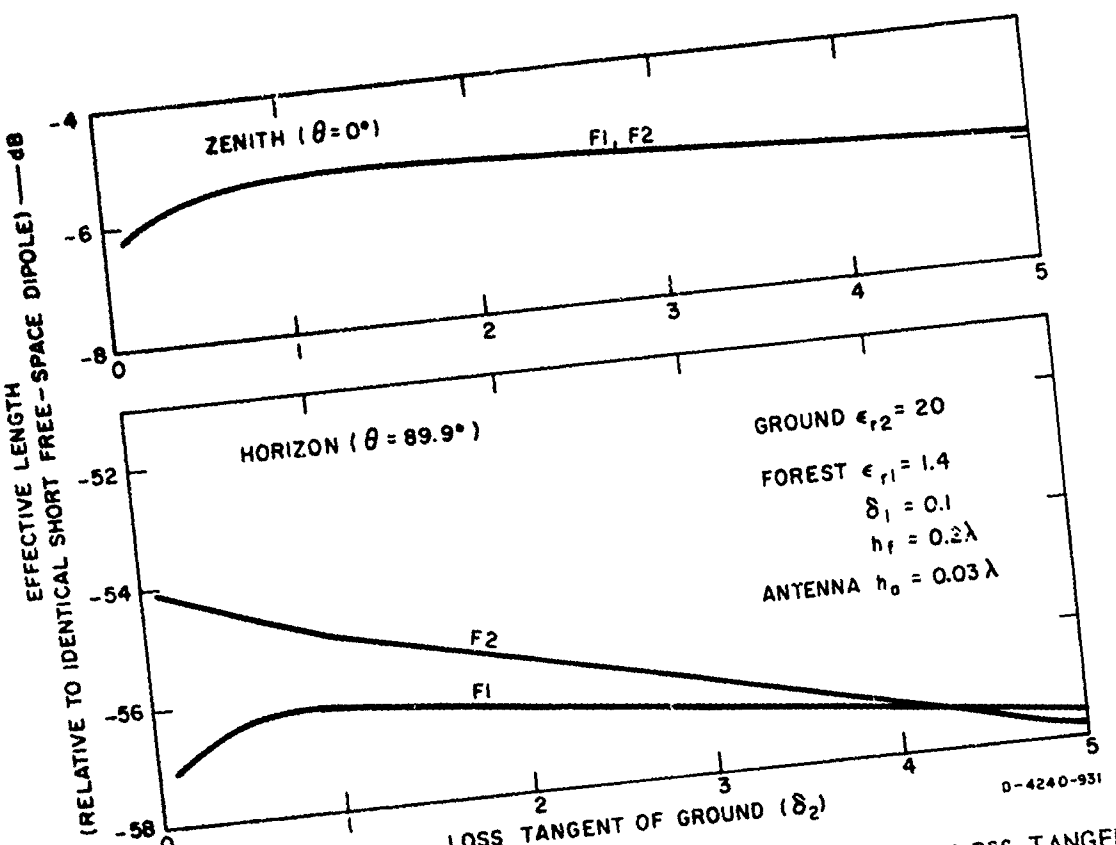

FIG. 14 EFFECTIVE ANTENNA LENGTH AS A FUNCTION OF GROUND LOSS TANGENT

VI COMPARISON WITH MEASURED DATA

Few measured results exist with which the computed patterns can be compared. A measurement phase is under way on this project, however, and some preliminary results are available. Figure 15 shows a comparison of the measured antenna height-gain curve for an antenna over a flat field (no forest) with computed results. The antenna used for these measurements was a horizontal balanced dipole a half wavelength long. Since the antenna resistance differed considerably from that of an electrically short dipole, the measured input resistance was used in the antenna gain computations of Sec. IV, together with the computed radiation patterns, to obtain G_{dB}. The measured values of gain were obtained by comparing the strength of the received signal with that received on an identical antenna maintained at 40 feet above ground. The same antenna was used to transmit signals and to receive the signals reflected by the ionosphere, so that the two-way gain was measured. This value was then halved to give the more familiar one-way gain.[9] As can be seen, the agreement is quite good.

Figures 16 and 17 show a comparison of the measured and computed radiation patterns of an 8-Mc/s horizontal dipole 23 feet above ground. The measured values were taken from experiments performed on another phase of the current project.[10] Figure 16(a) is for an antenna in a clearing and Fig. 16(b) for one in a forest; Fig. 17 is a composite of these figures. Of particular significance are the crossover of the (directivity) functions F_1 from the open-field (solid curve in Fig. 17) to the forest (dashed curve) case and the similar behavior of the measured values. Note also that, at low elevation angles, the directivity pattern in both planes was enhanced* when the antenna was immersed in the forest, as predicted by the model. The foliage constants used in this application of the mathematical model were estimated from experimental measurements made in a similar conifer forest in Washington.[3]

* Relative to the open-field conditions.

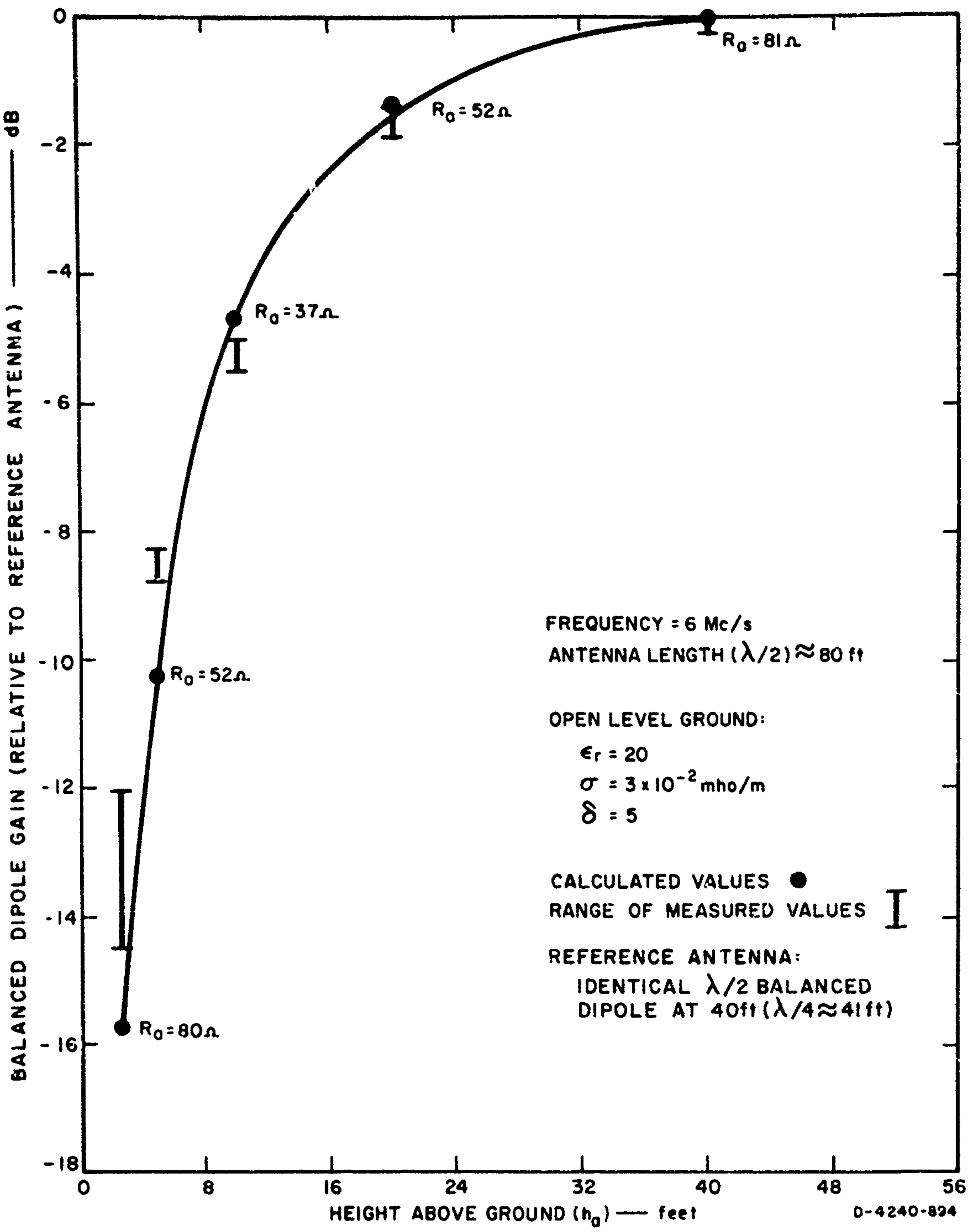

FIG. 15 COMPARISON OF CALCULATED AND MEASURED DIPOLE GAIN AS A FUNCTION OF HEIGHT ABOVE GOOD GROUND

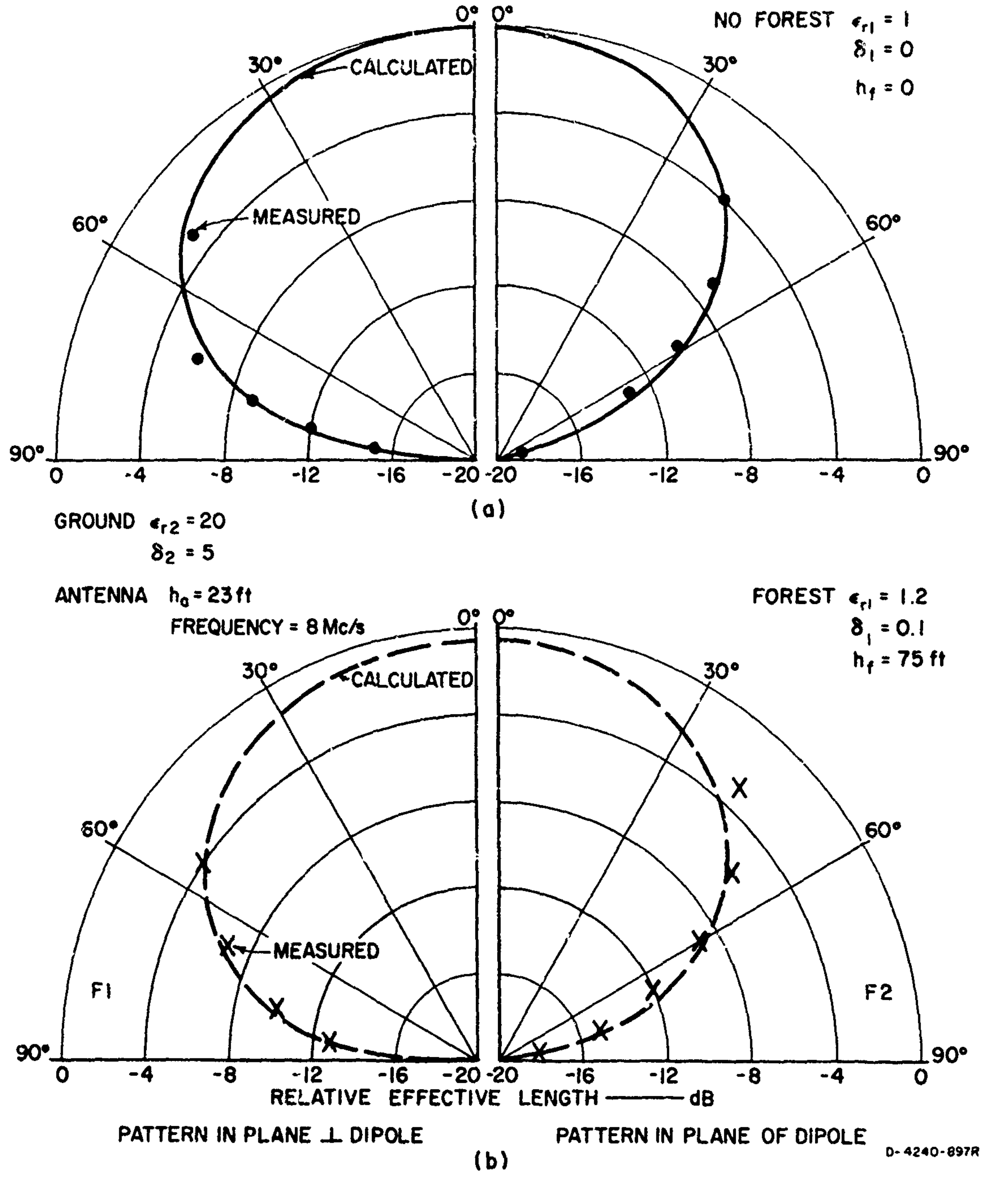

FIG. 16 EFFECTIVE LENGTH, MEASURED AND CALCULATED, FOR DIPOLE ANTENNA

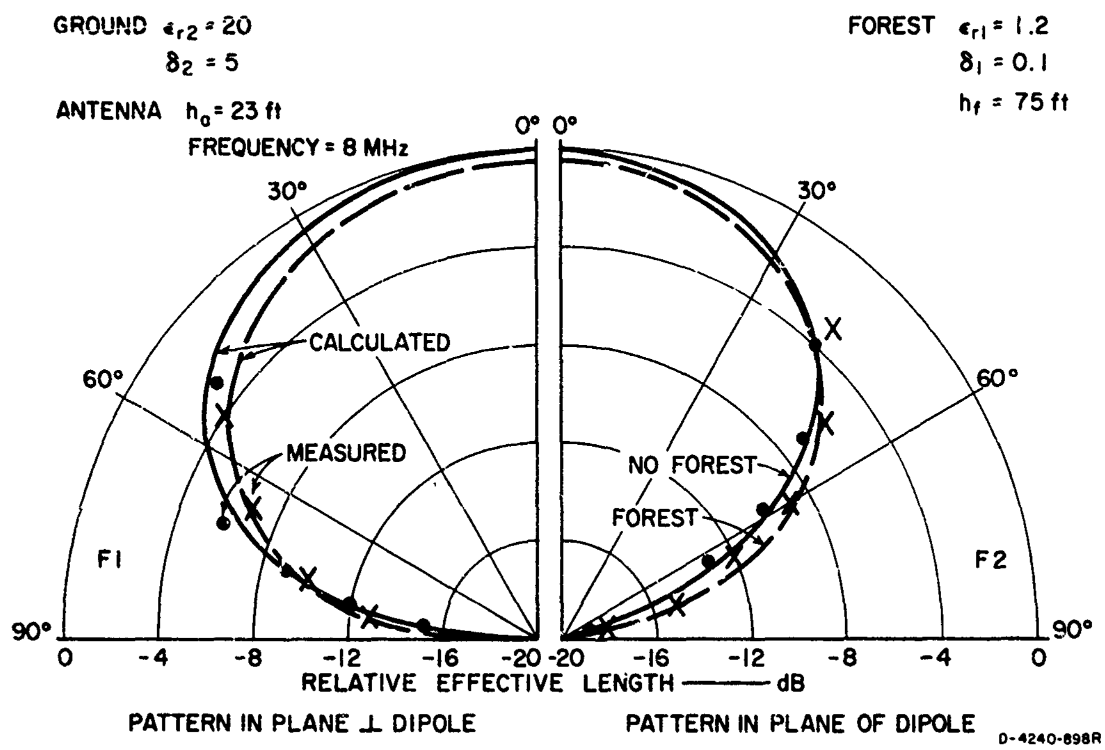

FIG. 17 COMPARISON OF MEASURED AND CALCULATED EFFECTIVE LENGTHS FOR DIPOLE IN FOREST AND IN OPEN

VII SYSTEMS CONSIDERATIONS

Some discussion of the systems aspect seems appropriate here, to relate this analysis to the complete picture. Without specifying our criterion of system performance, we can be sure that this criterion will be a monotonically increasing function of the received signal-to-noise ratio. Let us, then, examine the signal-to-noise ratio for a circuit similar to that depicted in Fig. 18 and see how we can use the results

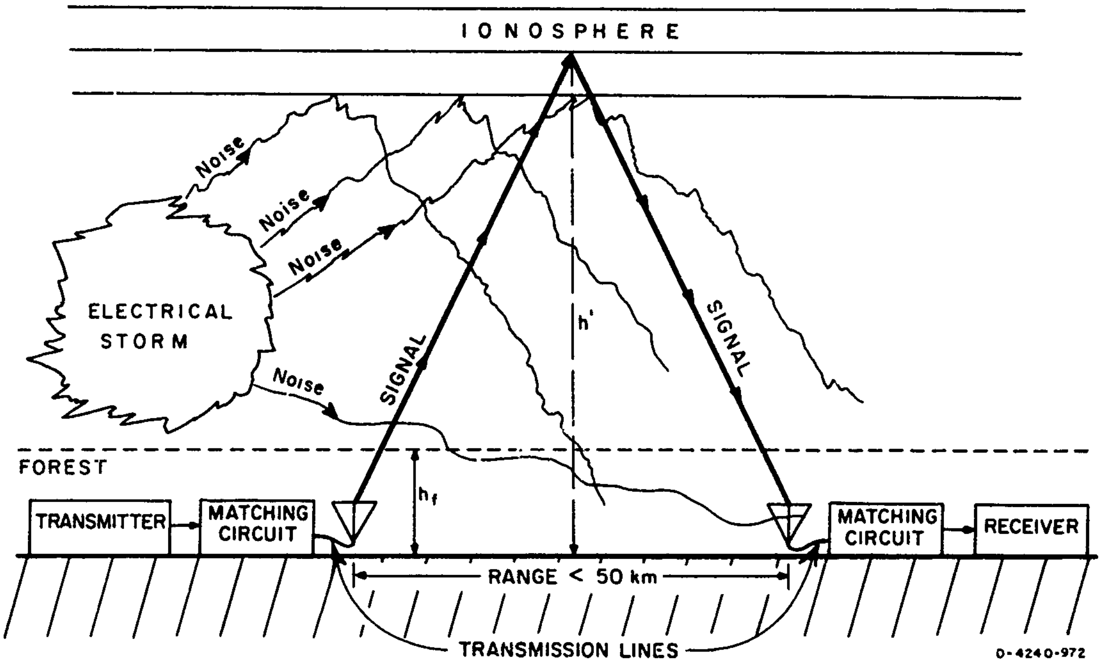

FIG. 18 SHORT-PATH HF SKYWAVE COMMUNICATION IN FOREST

of this analysis to compute, or at least to estimate, P_r. In a less quantitative manner we can see the effect of the various parameters that we have studied on the noise. After these considerations, perhaps the importance of the various parameters as they apply to the overall system performance will be more apparent.

The received signal power, P_r, is given by:

$$P_r = \frac{P_0 \lambda^2 \eta_t \eta_r G_t G_r \rho}{(8\pi h')^2} \quad ,$$

where

P_0 is the transmitter output power,

G_t and G_r are the transmitting and receiving antenna gains relative to an isotropic radiator in the direction of the ray between transmitter and receiver,

η_t and η_r are the power transfer efficiencies of the antenna matching circuits including transmission lines,[11]

ρ is the power reflection coefficient of the ionosphere, including attenuation and polarization losses,

h' is the virtual height of reflection which one would scale from a vertical-incidence ionogram for the frequency of interest (for ionospheric paths less than 50 km).[12]

The two quantities that specifically interest us here are the transmitting and receiving antenna gains, and we wish to examine the effect of the various parameters that determine these gains on the received signal power and on the received signal-to-noise ratio. Antenna length is not being considered here, and it does not affect the gain. The receiving and transmitting antenna gains are symmetrical in the equation for received power; hence the effect of changing one is identical to the effect of changing the other. This is not true for the signal-to-noise ratio.

It can be seen immediately that antenna height is the only parameter affecting the gain that is important in determining received signal power for short ionospheric paths, and reference to Figs. 7, 8, 9, and 15 will show the importance of this parameter.

As far as the received noise power is concerned, only the directivity of the receiving antenna has any appreciable effect. In the high-frequency band, atmospheric noise and interference dominate over internally generated receiver noise for all but extremely poor antenna-receiver combinations; hence the height of the receiving antenna is not very important. When this study was begun, it was hoped that a dipole antenna height could be found

that would reduce the noise more than the signal. This appeared to be possible, since the noise may arrive from any direction. An examination of the radiation patterns, however, indicates that we should expect to achieve, on the average, very little improvement in signal-to-noise ratio by a change in the height of the receiving antenna (such as lowering it into the foliage). Indeed, there might actually be degradation of receiver signal-to-noise ratio for the case where most of the noise is arriving at elevation angles near the horizon and the antenna is immersed in vegetation (see Fig. 17). This should be checked by experiment.

In the practical case, the effect of transmitting antenna height on received signal strength, and hence on received signal-to-noise ratio, is probably not quite as great as Figs. 8 and 9 would indicate. For one reason, if the antenna is very short so that the matching circuit efficiency is low, then the effect of ground proximity is to raise the input resistance and reduce the input reactance and thus to improve the matching circuit efficiency. This improvement in efficiency partially compensates for the reduced antenna gain. On the other hand, if the antenna is long enough to have a reasonable resistance to reactance ratio even in free space and thus to have a high matching circuit efficiency, then the change in input resistance with height is not as great as the curves of Vogler and Noble[5] indicate. Hence the gain function does not change so drastically as Fig. 8 would indicate. The improvement that can be achieved is quite significant, as reference to Fig. 15 for the case of a half-wavelength dipole will show; but for antenna heights greater than about $\lambda/10$ the improvement in system signal-to-noise ratio is only on the order of 3 dB. Thus the field communicator employing a horizontal dipole in the lower part of the HF band should try to get his antenna as high as is practical (but no higher than about $\lambda/4$). The antenna should be higher than $\lambda/10$ if possible, but he might want to carefully consider his situation and other needs before raising his antenna over twice that high to reach the often-recommended value of $\lambda/4$.[13]

VIII CONCLUSIONS

The primary purpose of the work undertaken thus far, involving the modeling study of the dipole antenna in vegetation, was to determine the relative importance of the six variables in this simple dielectric-slab model. A rigorous solution of the boundary value problem was made, and each of these parameters was varied over realistic ranges to determine its effect on the gain of a dipole antenna at the zenith and at the horizon. This study revealed that the antenna height above ground had the greatest effect upon the gain at both zenith and horizon, and it was observed that antenna height is usually the only variable over which the field communicator has much control. Except for the effect of forest height and dielectric constant on gain near the horizon, all other variables apparently had a rather negligible effect (on the order of a few decibels). In order of decreasing significance, the remaining variables are: forest loss tangent (δ_1), earth dielectric constant (ϵ'_{r2}), and earth loss tangent (δ_2). It must be cautioned, however, that these variables were not allowed to range over all possible values, because the realistic ranges for the foliage constants were determined from the rather scant literature.[14] Subsequent preliminary measurements with experimental equipment for sensing vegetation constants indicate that the loss tangent of the dense vegetation (calculated for the lower part of the HF band) may not have been allowed to vary to large enough values: Values of δ as large as 0.3 have been obtained at 4 Mc/s in vegetation of medium density.[3]

It was possible, however, to evaluate (as a limiting case) the performance of the horizontal dipole antenna in the absence of any vegetation, by permitting the electrical properties for the forest slab to assume the values for free space. The measured height-gain function for a balanced 6-Mc/s resonant dipole compared very well with values calculated by employing this modeling technique. This check of the measured height-gain function at the zenith[9] in the absence of vegetation is an encouraging demonstration of the validity of the model for that case.

It was also possible to compare the calculations of gain as a function of elevation angle for both F_1 (the pattern in the plane perpendicular to the dipole) and F_2 (the pattern in the plane parallel to the dipole) for antennas at a fixed height, with the values measured using the airborne Xeledop technique.[10,15] This comparison was performed for the case of an 8-Mc/s half-wave dipole at 23 feet above ground, located first in an open, level, newly plowed field (Lodi, California) and later in a CONUS conifer forest (Lake Almanor, California). Even though the model employed in this report has assumed a short dipole (linear current distribution) and the measured values were for a full-scale half-wave dipole (having an approximately sinusoidal current distribution), the results for both environments compared quite favorably with the model (see Fig. 17).

The simplest model (single-ray propagation through a simple lossy slab) for the change of an antenna directivity pattern as the antenna is moved from the open into a forest medium would predict that the antenna gain in the forest should decrease according to the secant function. Thus there would be a slight decrease in gain at vertical incidence due to the non-zero height of the lossy forest,* where the antenna immersed in the vegetation exhibits less gain than its open terrain value; and as the elevation angle is decreased the gain continues to fall off monotonically. Significantly, the more complex model presented in this report predicts a crossover in the F_1 pattern between the gain function for a dipole in the open and that for the antenna in the vegetation, and indeed this crossover is observed in a comparison of the measured data from the Lodi (open) site and the Lake Almanor (forest) site. At low elevation angles, the dipole gain in the forest was actually greater than it was in the open for both planes of reference (F_1 and F_2).†

A brief consideration of the systems aspects—included primarily to relate the work described in this report to the overall HF communication problem on short paths in the tropics—has indicated that antenna height is the key variable affecting received signal power. But a check of both the measured and the calculated values for the case of open terrain has indicated that elevating the transmitting antenna higher than $\lambda/10$ on

* Gain could be normalized to be equivalent at the zenith so that the directivity functions, F, could be more conveniently compared.

† For the case under consideration here, the change in gain is the same as the change in the field functions (or the effective length functions) squared.

upward toward the typically recommended value of $\lambda/4$ adds, at the most, on the order of 3 dB. Significant gains are made, however, by elevating the transmitting antenna to at least $\lambda/10$, with the relative improvement with incremental height increase becoming smaller monotonically as the antenna is raised from the ground.

In regarding the dipole as a receiving antenna, there is no apparent advantage to trying to improve the signal-to-noise ratio by placing an antenna in dense vegetation when it is employed for short ionospheric paths—indeed there may be a slight disadvantage. This should be checked by experiment.

Thus it appears that the model for the electrically short horizontal dipole agrees well with measured results in the lower part of the HF band for a full-scale resonant dipole in the direction of the zenith for the degenerate case of no trees, and that it also agrees well with dipole directivity patterns for elevation angles ($90° - \theta$) between approximately 5 and 55 degrees.

APPENDIX

SYMBOLS USED IN THIS REPORT

α_1	Real part of propagation constant in Region 1 (forest)
α_2	Real part of propagation constant in Region 2 (earth)
β_1	Imaginary part of propagation constant in Region 1 (forest)
β_2	Imaginary part of propagation constant in Region 2 (earth)
γ_0	Propagation constant in Region 0 (space above forest)
γ_1	Complex propagation constant in Region 1 (forest)
γ_2	Complex propagation constant in Region 2 (earth)
δ_1	Loss tangent in Region 1 (forest)
δ_2	Loss tangent in Region 2 (earth)
ϵ_0	Dielectric constant of free space (region above forest)
ϵ_{r1}	Complex relative dielectric constant in Region 1 (forest)
ϵ_{r2}	Complex relative dielectric constant in Region 2 (earth)
ϵ'_{r1}	Real part of ϵ_{r1}
ϵ'_{r2}	Real part of ϵ_{r2}
ζ	Impedance of medium in which antenna is immersed
ζ_0	Intrinsic impedance of free space (region above forest)
λ	Wavelength
η	Power transfer efficiency
μ_0	Magnetic permeability of free space (all three regions)
A, B, R, T, W, C_1, C_2	Arbitrary coefficients as defined by equations
D_a	Antenna effective aperture
$D(\theta,\phi)$	Directivity function
E_{1x}, E_{1y}, E_{1z}	Components of electric field in Region 1

$\overline{E}(\theta,\phi)$ Electric field at distance r in the θ, ϕ direction

$\overline{E}_r$ Reflected component of electric field

$\overline{E}_i$ Incident component of electric field

$\overline{E}_0$ Electric field in Region 0 (space above forest)

$\overline{E}_1$ Electric field in Region 1 (forest)

$\overline{E}_2$ Electric field in Region 2 (earth)

$F_1(\theta)$ Field function as described (plane normal to transmitting dipole)

$F_2(\theta)$ Field function as described (in plane of transmitting dipole)

$G(\theta,\phi)$ Gain function

G_a Gain constant for a given antenna configuration

G_d Maximum of the gain function of a dipole in free space

G_t, G_r Transmitting and receiving antenna gains relative to an isotropic radiator in the direction of the ray between transmitter and receiver

$G_1(\theta,\phi)$ Gain function in plane normal to transmitting dipole

$G_2(\theta,\phi)$ Gain function in plane of transmitting dipole

h' Virtual height of reflection from an ionospheric layer

$\overline{h}(\theta,\phi)$ Vector effective length of antenna

h_a Antenna height

$\overline{H}_r$ Reflected component of magnetic field intensity

$\overline{H}_i$ Incident component of magnetic field intensity

$\overline{H}_0$ Magnetic field intensity in Region 0 (space above forest)

$\overline{H}_1$ Magnetic field intensity in Region 1 (forest)

$\overline{H}_2$ Magnetic field intensity in Region 2 (earth)

I_0 Antenna current

k Wave number

k_0 Free-space wave number

h_f Height of forest dielectric slab

$p(\theta,\phi)$ Power density in transmitted wave

P Input power to the antenna

P_0 Transmitter output power

P_r	Received signal power
r	Distance from transmitting antenna phase center to point of measurement of electric field
ρ	Power reflection coefficient of the ionosphere
Ra	Input resistance of antenna
Rd	Input resistance of electrically short dipole in free space
Voc	Open-circuit antenna voltage
$\omega = 2\pi f$	Radian frequency
$\hat{x}, \hat{y}, \hat{z}$	Unit vectors in x, y, and z directions, respectively.

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13 ABSTRACT

A mathematical model of a short dipole antenna in a homogeneous, isotropic forest medium is developed. Height gain function and directivity patterns at HF are calculated for two cases, antenna in the open and in a forest, and these calculations are compared with some preliminary airborne measurements made with resonant dipoles. Excellent agreement between calculated and measured patterns and gain is obtained. Dipole gain at low elevation angles is found to increase in the forest (over the open-field case).

Permutation of the six parameters of the model (permittivity and loss tangent of both earth and forest, antenna height, and forest height) indicates that the effect of antenna height (h_a) is the most significant. Forest height and permittivity of the forest become important at the very low elevation angles and the loss tangent of the earth becomes important at low antenna heights ($h_a < \lambda/10$). The dielectric constant of the ground and loss tangent of the forest are apparently relatively unimportant variables when checked over the ranges that seem reasonable for tropical forests.

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	ROLE	WT	ROLE	WT	ROLE	WT
Model; lossy dielectric slabs						
Short dipole antenna						
Forest medium						
Relative dielectric constant (permittivity)						
Loss tangent						
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Antenna height						
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